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6. AUTHOR(S)
DR. JOHN A. GUBNER

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF CONNECTICUT
DEPARTMENT OF MATHEMATICS
STORRS, CT 06269

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NM
110 DUNCAN AVE, SUITE B115
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Aug. 31, 1996 Final Technical Report, July 1, 1992–June 30, 1996

Photon-Limited Image Detection Using Shot-Noise Models

Dr. John A. Gubner

Department of Electrical and Computer Engineering
University of Wisconsin–Madison
Madison, WI 53706–1691

Air Force Office of Scientific Research
110 Duncan Avenue, Suite B115
Bolling AFB, DC 20332

Distribution Unlimited

The objective of this research continues to be the study of shot-noise models and their application to the development of computationally feasible procedures for image-detection problems. Also of interest is the performance evaluation of these procedures. These efforts are motivated by applications to low-light-level imaging as would occur in low-dose x-ray exposures or in night vision systems. Results are also be applicable to photon-limited optical communication systems [2] and to optical neural networks [7].

Considerable progress has been made in understanding shot noise. The three major results of our research are (i) methods for computing shot-noise distributions when both the intensity function and the system impulse response are known [6], [8]; (ii) methods for estimating an unknown intensity when only the impulse response is known [5]; and (iii) methods for jointly estimating the intensity and the impulse response when both are unknown (a type of blind deconvolution) [9].

shot noise, Poisson process, intensity estimation, blind deconvolution 5

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Due August 31, 1996

Photon-Limited Image Detection Using Shot-Noise Models

J. A. Gubner, Associate Professor, Principal Investigator

Department of Electrical and Computer Engineering
University of Wisconsin–Madison
Madison, WI 53706–1691

Objectives

The objective of this research continues to be the study of shot-noise models and their application to the development of computationally feasible procedures for image-detection problems. We are also interested in the performance evaluation of these procedures. These efforts are motivated by applications to low-light-level imaging as would occur in low-dose x-ray exposures or in night vision systems. Our results are also be applicable to photon-limited optical communication systems and to optical neural networks.

Status of Effort

Considerable progress has been made in understanding shot noise. The three major results of our research are (i) methods for computing shot-noise distributions when both the intensity function and the system impulse response are known; (ii) methods for estimating an unknown intensity when only the impulse response is known; and (iii) methods for jointly estimating the intensity and the impulse response when both are unknown (a type of blind deconvolution).

These results are discussed in more detail below along with other work supported by this grant.

Accomplishments/New Findings

- Shot noise that arises in spectroscopy has an underlying intensity which is a positive linear combination of Voigt functions. A Voigt function is the convolution of a Gaussian probability density and a Cauchy, or Lorentzian, probability density. Because Voigt functions arise in many different contexts, such as nuclear reactor theory, atmospheric transmittance, and spectroscopy, there has been much interest in computing them. In [1] (see the Publications section below) a new series for approximating Voigt functions is presented, including error bounds. An asymptotic expansion for large argument values is also given, along with error bounds.
- In many applications, one does not know the underlying intensity of the shot noise, or even the system impulse response. For the case when the system impulse response is known, the paper [5] uses a regularization technique involving a pair of regularization parameters. A new method for selecting the pair of parameters is presented and compared with the minimum unbiased risk method. Although both methods recover the detail in the intensity function, the new method does a better job at suppressing spurious oscillations.

  For the case when both the intensity function and the system impulse response are unknown (blind estimation), the paper [9] (which was revised during 95–96) first estimates a histogram of the underlying point process and then constructs a kernel estimate of the intensity. The estimate of the unknown impulse response is constructed via a regularized back-substitution of a discrete-time convolution with the estimated histogram.
- Even if the shot-noise intensity and system impulse response are known, it is quite difficult to compute the cumulative distribution and density for shot noise. Being able to compute these functions will enable the construction of detectors and the evaluation of their performance. In [6], the computation of the cumulative distribution (cdf), the complementary cdf (ccdf), and the density of certain shot-noise random variables is discussed. After subtracting off a few terms that can be computed in closed form, what remains can be approximated by a general method for approximating samples of a cdf or ccdf by summing a Fourier series whose coefficients are modulated samples of their characteristic function. To approximate the density, a spline is fit to the cdf samples and then differentiated. When the density has

corners, it is important that the spline have coincident knots at these locations. For shot-noise densities, these locations are easily identified.

In 95–96, we have studied Monte-Carlo estimation of shot-noise cdfs for comparison with the above method. Although Monte-Carlo methods require more computation, we found that they could be speeded up using a change of measure in which the underlying Poisson process is simulated with an alternative intensity.

The methods of paper [6] suggested a similar approach could be used to recover the cdf and ccdf of a counting distribution from its characteristic function. This result is reported in [8] and was used to evaluate the shot-noise limited performance of an optical neural network [7].

- Shot-noise with random impulse response arises in the study of avalanche photodiodes. The effects of dead space on the bit-error rate for an optical receiver have been studied in [2]. In particular, it is found that dead space enhances the performance at relatively low data rates, and degrades performance at high data rates. Thus, in order to correctly predict performance of high-data-rate systems, it is critical to account for the dead-space effect.
- Other research supported by this grant included an investigation into wavelets for discrete-time periodic signals [4], and the capacity region of the multiple-access arbitrarily varying channel [3].

Personnel Supported

- Faculty (1): John A. Gubner, Associate Professor, Principal Investigator
- Graduate Students (1): Raúl E. Sequeira (dissertation appears in [5] and [9])
- Post-Docs (1): Raúl E. Sequeira

Publications

[1] J. A. Gubner, "A new series for approximating Voigt functions," *Journal of Physics A: Mathematical and General*, vol. 27, no. 19, pp. L745–L749, Oct. 1994.

[2] M. M. Hayat, B. E. A. Saleh, and J. A. Gubner, "Bit-error rates for optical receivers using avalanche photodiodes with dead space," *IEEE Transactions on Communications*, vol. 43, no. 1, pp. 99–106, Jan. 1995.

[3] J. A. Gubner and B. L. Hughes, "Nonconvexity of the capacity region of the multiple-access arbitrarily varying channel subject to constraints," *IEEE Transactions on Information Theory*, vol. 41, no. 1, pp. 3–13, Jan. 1995.

[4] J. A. Gubner and W.-B. Chang, "Wavelet transforms for discrete-time periodic signals," *Signal Processing*, vol. 42, no. 2. pp. 167–180, Mar. 1995.

[5] R. E. Sequeira and J. A. Gubner "Intensity estimation from shot-noise data," *IEEE Transactions on Signal Processing*, vol. 43, no. 6, pp. 1527–1531, June 1995.

[6] J. A. Gubner, "Computation of shot-noise probability distributions and densities," *SIAM Journal on Scientific Computing*, vol. 17, no. 3, pp. 750–761, May 1996.

[7] M. M. Hayat, B. E. A. Saleh, and J. A. Gubner, "Shot-noise-limited performance of optical neural networks," *IEEE Transactions on Neural Networks*, vol. 7, no. 3, pp. 700–708, May 1996.

[8] J. A. Gubner and M. M. Hayat, "A method to recover counting distributions from their characteristic functions," *IEEE Signal Processing Letters*, vol. 3, no. 6, pp. 184–186, June 1996.

[9] R. E. Sequeira and J. A. Gubner "Blind intensity estimation from shot-noise data," *IEEE Transactions on Signal Processing*, in press.

Interactions/Transitions

a. Participation/Presentations at Meetings, Conferences, Seminars, etc.

1. J. A. Gubner "A method for computing shot-noise cumulative distributions and densities," *Proceedings of the 1993 IEEE International Symposium on Information Theory,* San Antonio, TX, p. 309, Jan. 1993.
2. J. A. Gubner "A method to recover counting distributions from their characteristic functions," *Conference on Applied Probability in Engineering, Computer, and Communication Sciences (Abstracts),* Paris, France, p. 195, June 1993.
3. J. A. Gubner and B. L. Hughes, "Nonconvexity of the capacity region of the multiple-access arbitrarily varying channel subject to constraints," *Proceedings of the 1994 IEEE International Symposium on Information Theory,* Trondheim, Norway, p. 53, June 1994.
4. J. A. Gubner, "Intensity estimation from shot-noise observations." AFOSR Probability and Statistics Contractors' Meeting, Corvallis, OR, July 22–24, 1994.
5. M. M. Hayat, B. E. A. Saleh, and J. A. Gubner, "Quantum limited performance of optical neural networks," *Optical Society of America Annual Meeting Technical Digest,* Houston, TX, Oct. 1994.
6. R. E. Sequeira and J. A. Gubner "Intensity estimation from shot-noise data," *Conference on Image Reconstruction and Restoration,* San Diego, CA, July 1994.
7. J. A. Gubner "The capacity regions of the multiple-access arbitrarily varying channel." Supercomputing Research Center, Bowie, MD, Nov. 4, 1994.
8. M. M. Hayat, B. E. A. Saleh, and J. A. Gubner, "Quantum-limited image estimation using twin-photon beams," *Proceedings of the SPIE International Symposium on Optical Science, Engineering, and Instrumentation,* Denver, CO, Aug. 1996.

b. Consultative and Advisory Functions.
None.

c. Transitions.
None.

New Discoveries

None.

Honors/Awards

None.